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The provenance of the Devonian Old Red Sandstone of the Dingle Peninsula, SW Ireland – the earliest record of Laurentian and peri-Gondwanan sediment mixing in Ireland.

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Abstract

The Lower Old Red Sandstone (LORS) in southern Ireland is hosted in the Lower Devonian Dingle Basin which lies immediately south of the Iapetus Suture on the Dingle Peninsula, County Kerry. The basin developed as a post-Caledonian pull-apart structure prior to Acadian deformation which in turn was followed by end-Carboniferous Variscan deformation. Detrital zircon U-Th-Pb geochronology is complimented by mica Ar-Ar and apatite U-Pb geochronology to gain a comprehensive understanding of the provenance of the Lower Devonian LORS of the Dingle Basin and assess contributions of major tectonic components (e.g. Laurentia, Ganderia). Sedimentary rocks in the LORS have similar detrital zircon age distributions which are dominated by ca. 1.2 Ga zircons as well as late Neoproterozoic grains. This indicates a dominant contribution of detritus of Laurentian affinity as well as contributions from westerly and southerly derived Ganderian detritus. Caledonian uplift of the area north of the Iapetus Suture would have facilitated a large contribution of (peri-)Laurentian material. The Upper Old Red Sandstone on the Dingle Peninsula has a distinctly different detrital zircon character including few late Neoproterozoic zircons and abundant zircons of ca. 1.05 Ga age, indicating sediment derivation only from Laurentia and no recycling from the LORS.

Supplementary material: the full detrital U-Pb zircon (Table-1) and apatite (Table-2) analytical dataset as well as revised detrital mica age dataset (Table-3) is available at xxxxx.

The Dingle Basin in County Kerry, southwest Ireland represents the only record of Early Devonian sedimentation south of the Iapetus Suture in Ireland. Its structure records a critical period in the tectonic history and development of Ireland, having been affected by both the Acadian and Variscan Orogenies (Meere & Mulchrone 2006). Furthermore, the basin’s sedimentary rocks offer an opportunity to understand the palaeogeography of the basin, possibly recording Grampian to Late Caledonian (430-420 Ma) detrital input following the final Silurian accretion of Ganderia to the margin of Laurentia.

Existing provenance studies (e.g. Todd 2000; Ennis *et al.* 2015) have greatly improved our understanding of the development and palaeogeography of the Dingle Basin. However, a comprehensive investigation utilising detrital single-grain techniques has yet to be undertaken. Such a study would serve to elucidate regional sediment source contributions in a basin which is intimately associated with the Iapetus Suture (Todd 2000) – arguably the most important structural entity for in the Phanerozoic tectonic history of Ireland.

This study provides the first multiproxy (zircon, apatite, mica) single-grain datasets from the area, with the aim of determining the provenance of the Lower Old Red Sandstone (LORS) in the Dingle Group of the Lower Devonian Dingle Basin and assessing the roles of Laurentian and peri-Gondwanan domains in contributing detritus. The study also considers the detrital zircon provenance of the Upper Old Red Sandstone (UORS) on the Dingle Peninsula.

Regional Geology and Review of Terranes in the British Isles

The oldest potential source of detrital zircons lies to the north of the Iapetus Suture Zone (ISZ) in the form of the long-lived Laurentian craton (Fig. 1). A compilation of existing detrital zircon data of known Laurentian sources (Fig. 2) shows three broad peaks that correspond to major crust-forming events which contributed to the formation of Laurentia (Cawood *et al.* 2007). These peaks occur in the Archaean, Palaeoproterozoic and Mesoproterozoic recording essentially uninterrupted zircon production from 1.9 Ga to 0.9 Ga. A major characteristic of detrital zircon distributions from this sector of the Laurentian continent is the absence of zircons of late Neoproterozoic age due to the absence of an active margin on the Laurentian continent at this time (Pointon *et al.* 2012). The Rhinns Complex on the island of Inishtrahull off the north coast of County Donegal and the Annagh Gneiss

Complex in County Mayo comprise the exposed Proterozoic Laurentian basement in Ireland, and are also the oldest rocks exposed in Ireland. The Grenville Orogeny, represented by the large peak in late Mesoproterozoic zircon ages in Figure 2, is recorded in the Annagh Gneiss Complex by the 1.17 Ga Doolough gneiss, the 1.01 Ga Doolough Granite and by 0.99 to 0.96 Ga late orogenic pegmatites and migmatitic leucosomes (Daly 1996). A variety of marine sedimentary (e.g. Clew Bay Complex), ocean-arc-volcanic (e.g. Lough Nafooey Arc – see (Chew *et al.* 2007) and ophiolitic rocks (e.g. Deer Park Complex) make up the material accreted to the margin of Laurentia during the Grampian Orogeny (465-475 Ma) in Ireland which represents the early stage of the Caledonian orogenic cycle (Chew & Stillman 2009). This was followed by sinistral transpressive docking of a peri-Gondwanan terrane to the newly-accreted Laurentian margin (Dewey & Strachan 2003).

The term `peri-Gondwanide' was first proposed by Van Der Voo (1988) to describe a number of tectonostratigraphic elements which existed as terranes in the Iapetus Ocean during the Ordovician period. Using palaeomagnetic evidence, Van Der Voo (1988) suggested that these terranes were proximal to northwest African Gondwana, rather than Laurentia. This has since been supported by other studies (see Nance *et al.* 2008, and references therein). We use the term *domain* to refer to tectonostratigraphic units consisting of one or more terranes (Hibbard *et al.* 2007). Peri-Gondwanan domains include Avalonia, Ganderia, Megumia, Carolinia in present-day North America, and Avalonia and Cadomia (including Iberia, Bohemia and Armorica) in Europe (Nance *et al.* 2008). Those domains that had the potential, given their Devonian positions relative to southern Ireland, to provide sediment to the basin being investigated include Avalonia, Ganderia and Megumia. For a comprehensive review of peri-Gondwanan terranes, the reader is referred to Nance *et al.* (2008). The correlation of the Meguma terrane to the Harlech Dome is discussed by Waldron *et al.* (2011), White *et al.* (2012) and Nance *et al.* (2015).

The main rock exposures of pre-Devonian basement south of the Iapetus Suture Zone in Ireland are found in the Leinster Massif in the southeastern part of the island. The massif hosts a number of Cambrian to Silurian volcanic and sedimentary units intruded by Caledonian-Acadian granites. There has been wide acceptance that pre-Silurian southern Ireland represents part of Avalonia (e.g. Van Der Voo 1983; Livermore *et al.* 1985; Van Der Voo 1988; Pickering *et al.* 1988; Ford *et al.* 1992; Cocks *et al.* 1997; McConnell & Morris 1997; Keppie *et al.* 2003; Tyrrell *et al.* 2007; Woodcock & Strachan 2012; Fullea *et al.* 2014; Todd 2015), but others have suggested linkages to different peri-Gondwanan domains. One school of thought contends that southern Ireland, Wales and southern England formed part of a number of terranes that collectively formed Cadomia (e.g. Soper & Hutton 1984; Max *et al.* 1990).

Kennedy (1979) first implied that southern Ireland is a trans-Atlantic extension of Ganderia. Van Staal *et al.* (1996) (and references therein) extend the Gander Zone of Newfoundland, where Ganderia was first described, into Ireland, Wales, England and the Isle of Man. As evidence of this they cited a correlation of Cambrian and Ordovician clastic successions, a similarity of overstepping successions, juxtaposition of mafic to ultramafic, possibly ophiolitic rocks (e.g. Rosslare Complex) and a similarity in fossil fauna. This extension of Ganderia into southern Ireland is further supported by Van Staal *et al.* (1998) who suggest that Avalonia and Ganderia may have become juxtaposed at least during the late Cambrian. If this is the case then it was an amalgamated Avalonia-Ganderia microcontinent that collided with Laurentia during the Caledonian Orogeny. More recently, Waldron *et* *al.* (2014) have drawn similarities between detrital zircon ages from Monian Composite Terrane (county Wexford) and Leinster-Lakesman samples and samples analysed by Fyffe *et al.* (2009) for Ganderia in New Brunswick and Maine. The difference between Ganderian detrital zircon samples from Cambrian sedimentary rocks and West Avalonian samples is that the latter are lacking in Mesoproterozoic and Palaeoproterozoic zircons (Waldron *et al.* 2014). Waldron *et al.* (2014) attribute these Mesoproterozoic and Palaeoproterozoic zircons in Ganderian sediments to a possible Amazonian source in West Gondwana.

Distinguishing between Avalonia and Ganderia by detrital zircon populations alone is difficult (Fig. 2). Stratigraphic, faunal and other isotopic evidence is required, as exemplified in a review of the East Avalonian terranes by Schofield *et al.* (2016). They use geochronological data as well as magmatic whole-rock Sm-Nd and O-isotopes to show that what is currently viewed as East Avalonian basement in England has closer isotopic and age affinities to Ganderia than to West Avalonia. Elimination of East Avalonia in the British Isles simplifies the interpretation of the provenance of Neoproterozoic detrital zircons in Devonian sedimentary rocks in the region. Although Ganderia is the most proximal potential source of Neoproterozoic zircons, one cannot eliminate the possible detrital influence from other peri-Gondwanan sources.

Waldron *et al.* (2011) proposed that the Cambrian successions of the Meguma terrane of Nova Scotia and the Harlech Dome of Wales be considered a single palaeogeographical domain which they named ‘Megumia’. They show that detrital zircon age distributions from the Harlech Dome have greater similarity to those in the Meguma terrane than those in Avalonia. The major difference in detrital zircon age distributions between Megumia and Avalonia is the significant presence of 1.95

to 2.1 Ga zircons in Megumia and the lack thereof in Avalonia. These zircon ages are believed to be associated with Eburnean orogenic magmatic activity (Waldron *et al.* 2011). For the purpose of this study, a significant contribution of Neoproterozoic zircon grains to the sediments under investigation is used predominantly as a tool to distinguish between peri-Gondwana-derived and Laurentia-derived zircons, due to the fact that Laurentia is not known to have any major source of Neoproterozoic zircons (Fig. 2). Furthermore, given the Devonian age and tectonic setting of the sediments, it is likely that they represent heterogeneous source areas. However, the reader is urged to bear in mind the complexities associated with sources of Neoproterozoic zircons in the British Isles, as described above.

The Grampian Orogeny, which occurred in the Ordovician period, is considered to be the first stage of the Caledonian orogenic cycle (Chew & Stillman 2009) and records the collision of an oceanic arc (recognised in Ireland as the Lough Nafooey Arc) with the Laurentian margin (Chew & Strachan 2014). Ordovician sediments from the South Mayo Trough record dominant input of zircons in the age range ca. 490 to ca. 467 Ma (McConnell *et al.* 2009). However, this range bears two populations, one around 487 Ma and one between ca. 474 and ca. 467 Ma, interpreted by McConnell *et al.* (2009) to be sourced from the Lough Nafooey Arc/Clew Bay Complex and the Connemara orthogneiss suite respectively. The Tyrone Igneous Complex is also of similar age to the Connemara suite (Cooper *et al.* 2011). The Grangegeeth volcanic terrane in eastern Ireland has a maximum age of ca. 465 Ma and inherited zircon within it indicate that it is of Laurentian origin, perhaps being related to the Tyrone Igneous Complex (McConnell *et al.* 2010). Its anomalous position south of the Southern Uplands – Longford Down terrane is attributed to transpressive strike-slip deformation in Middle Silurian times

(McConnell *et al.* 2010). To the south of the Grangegeeth terrane lies the Bellewstown terrane (Fig. 1. Regional map of the British Isles showing the major terranes of Ireland. The rectangle indicates the study area shown in Figure 3). This terrane is considered part of the Ganderian margin and zircons dated from a sandstone within a volcanogenic breccia place the age of volcanism in the terrane at ca. 474 Ma (McConnell *et al.* 2015).

Plagiogranite boulders from Silurian conglomerates which lie unconformably upon the Lough Nafooey Group are considered to be sourced from the Lough Nafooey Arc (Chew *et al.* 2007). U-Pb zircon ages of around 490 Ma from these boulders, supported by Nd-isotope data, led Chew *et al.* (2007) to conclude that the arc had encountered Laurentian margin sediments by this time. This represents a source of Early Ordovician detrital zircons. The Southern Uplands – Longford Down terrane predominantly consists of Ordovician to Silurian metasedimentary rocks that were originally deposited in the Iapetus Ocean on the margin of Laurentia and were subsequently accreted to this margin (McConnell *et al.* 2016; Waldron *et al.* 2008). On the Irish side, McConnell *et al.* (2016) found that these sediments contained Proterozoic zircons indicative of a Laurentian origin. In addition, their samples contained an abundance of Early to Middle Ordovician zircons which they interpret as representing a volcanic arc source (e.g. Tryrone Igneous Complex, Lough Nafooey Arc). On the Scottish side, Waldron *et al.* (2008) and Waldron *et al.* (2014) found that the majority of detrital zircons are of Proterozoic age and sourced from Laurentia. Generally, samples from these studies produced fewer Early to Middle Ordovician zircons relative to those from the Irish side of the terrane.

Another potentially important Ordovician zircon source occurs in the Duncannon and Ribband Groups in the Leinster Massif. The minor calc-alkaline volcanic rocks in the Ribband Group represent arc development during initial stages of subduction of the Iapetus Ocean crust beneath Ganderia (East Avalonia) in Tremadocian times (Woodcock 2012). The Duncannon Group volcanic suite consists of basalts and rhyolites, extruded in Caradoc times (Sandbian-Katian) which is considered indicative of a back-arc region (Woodcock 2012). These volcanic suites have not yet been isotopically dated and their ages are largely constrained by faunal evidence in associated sedimentary successions (e.g. Owen & Parkes 2000).

The final welding of Ganderia to the margin of Laurentia, which included an accreted ocean arc following the Grampian Orogeny, was achieved during the Caledonian Orogeny, by about 430-425 Ma (Mac Niocaill 2000; Waldron *et al.* 2014). However, abundant evidence of Late Caledonian (including Acadian, *sensu* Chew & Stillman 2009) magmatism exists in the form of widely distributed intrusions in Ireland and Britain. These range in age from ca. 430 Ma to 380 Ma (Fig. 2). An example of such an intrusion, which has been proposed as a proximal source of detritus to the Munster Basin (e.g. Penney 1980) and which represents the age of the majority of these intrusions (Fig. 2), is the Leinster granite batholith. O'Connor *et al.* (1989) obtained a U-Pb monazite age of 405 ± 2 Ma for the batholith. However, recent work by Fritschle *et al.* (2017) shows that it was emplaced over an extended period from ca. 417 Ma to 405 Ma. Vermeulen *et al*. (2000) have shown, by seismic analysis of southern Ireland, that the UORS south of the Killarney-Mallow Fault Zone is likely to be concealing a granitic body. Such an interpretation has been suggested by other studies (e.g. Ford *et al*. 1991; Meere 1995; Masson *et al*. 1998; Vermeulen *et al*. 2000; Todd 2000). Todd (2000) suggested that, based on clast analysis of the Trabeg Conglomerate Formation, a granite body similar to the Leinster Batholith was exposed in the southern hinterlands of the Dingle Basin during its development and that the Leinster terrane therefore extends westward following Caledonian trends. Other examples of intrusives of Late Caledonian age in Ireland include the Donegal (418-388 Ma), Galway (412-380 Ma) and Newry Granites (403-387 Ma) and the Carnsore and Saltees Granites (436-428 Ma). The age ranges presented above are, in most cases, the result of dating by multiple geochronogical techniques which yield different ages. The studies from which these ages are obtained are reviewed in Chew & Stillman (2009). The Newry Igneous Complex has recently been redated by Cooper *et al.* (2016) who showed that, like the Leinster Batholith, the complex was emplaced over a similarly extended period from 414 Ma to 407 Ma.

Following the closure of the Iapetus Ocean, a Silurian to Early Devonian period of sinistral transtension accommodated deposition of the LORS in the Dingle Basin and elsewhere in the southern British Isles (Todd 1989; Soper & Woodcock 2003). This Emsian transtension across the ISZ in Ireland and Britain possibly initiated emplacement of granites of similar age on either side of the ISZ (Brown *et al.* 2008; Cooper *et al.* 2016). The rocks of the Dingle Basin record an Emsian deformational event which is considered to be part of the Acadian orogenic episode (Todd 1989; Todd 2000; Meere & Mulchrone 2006; Todd 2015). Deformation occurred in a transpressive regime but its kinematic character in the Dingle Basin is debated (e.g. Todd 1989; Meere & Mulchrone 2006; Todd 2015) because the structural fabrics within the LORS are complicated by Carboniferous Variscan overprinting.

Local Geology and Sample Location

The majority of the rocks that crop out on the Dingle Peninsula, southwest Ireland, form part of the Lower to Middle Devonian Lower Old Red Sandstone of the Dingle Basin. Basement to this basin is also exposed on the peninsula in the form of the Ordovician Annascaul Formation and the Silurian Dunquin Group (Todd *et al.* 2000) (Fig. 3). These have been correlated with Ordovician and Silurian rocks in the Leinster Massif and therefore have a peri-Gondwanan affinity (Todd *et al.* 2000). The axis of the Dingle Basin approximates the regional northeast-southwest Caledonian trend in Ireland. The basin's sedimentary fill is complicated by a series of unconformities which separate five lithostratigraphic groups (Boyd & Sloan 2000). Todd *et al.* (1988) consider the main mechanism of subsidence to be in the form of a sinistral pull-apart structure. Meere and Mulchrone (2006) recognise two broad phases of extension: an Early Devonian phase that accommodated Dingle Basin sediments, and a Late Devonian to Carboniferous phase that accommodated the sediments of the Munster Basin. An intervening Middle Devonian transpression, likely recording the Acadian orogenic event (Dewey & Strachan 2003; Soper & Woodcock 2003), led Ennis *et al.* (2015) to consider the possibility of sedimentary recycling from the Dingle Basin into the Munster Basin. Such recycling of the Dingle Basin LORS into the UORS of the Munster Basin has also been suggested by Todd (2015).

Within the Dingle Basin, the Dingle Group, which is the most voluminous, represents a fluvial/alluvial environment in which axial (flowing from southwest to northeast along the basin axis) braid-plains and flood sheets, represented by the Eask, Coumeenoole, Slea Head and Ballymore Formations, were deposited by generally perennial axial river systems that flowed from the southwest (Todd 2000). These were abutted by alluvial fans, mainly represented by the Glashabeg Conglomerate Formation in the north and the Trabeg Conglomerate Formation in the south, that drained transversely into the basin (Todd 2000). Spores from the Eask and Slea Head Formation have yielded ages of Early Pragian and Early Emsian respectively (Higgs 1999). Two samples from the LORS of the Dingle Basin were taken from the Coumeenoole Formation and the overlying Slea Head Formation from the Dingle Group (Fig. 3) in close proximity to the locations of equivalent samples from Ennis *et al.* (2015).

Todd (2000) carried out an extensive study of clasts from the correlative Glashabeg Conglomerate, Slea Head and Trabeg Conglomerate formations in the Lower to Middle Devonian Dingle Basin. Based on the large number of mafic to intermediate volcanic clasts and the presence of limestone clasts in the Glashabeg Conglomerate Formation, he concluded that the source area was dominated by Ordovician volcanic rocks lying in close proximity to the north of the basin and likely intersecting the Iapetus Suture Zone. Rivers feeding the Slea Head Formation (and the conformably underlying Coumeenoole Formation, which has a similar palaeoflow direction) flowed axially through the basin toward the northeast, draining an area to the southwest (Todd 2000). Pebble clasts indicate sediment derivation from Silurian volcanic rocks and from an extension of the Leinster Massif basement (Todd 2000). The Trabeg Conglomerate Formation formed the southern flank of the Slea Head system and drained an area to the south and southwest of the basin which was made up of rocks similar to those observed in the Leinster Massif (Todd 2000).

Unconformably overlying the Dingle Group is the Smerwick Group, which consists of sedimentary rocks of aeolian and fluvial origin (Todd *et al.* 1988). The two groups are truncated by an unconformity that developed due to erosion during Late Emsian Acadian basin inversion (Meere & Mulchrone 2006). This was followed by deposition of the Pointagare Group, exposed only on the northern coast of the peninsula, and the Caherbla Group to the south which contains the Inch Conglomerate Formation. These formations are thought to have been deposited in Middle Devonian (Eifelian) times (Todd 2015, and references therein). Finally, the overstepping sandstone and conglomerate successions of the Slieve Mish Group were deposited during the Late Devonian and are considered by Williams (2000) to be a correlative of the Ballinskelligs Formation and equivalents in the Munster Basin. Sample AK17 was obtained from a pebbly sandstone of the fluvial to lacustrine (Todd 2015) Cappagh Sandstone Formation of the Slieve Mish Group.

Analytical procedures and sampling

The apatite U-Pb data were originally generated as part of a bedrock thermal history study utilising the apatite fission track (AFT) low-temperature thermochronometer (Cogné *et al*. 2014), because the laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) approach to AFT analysis permits U-Pb and AFT ages to be determined on the same grains during a single analytical session (Chew & Donelick 2012).The sampling and separation process is therefore different to the zircon separation process.

Zircon U-Pb

Data to produce the source ‘signals’ shown in Figure 2 were derived from a number of sources. Data from samples interpreted to be of Laurentian origin were sourced from Cawood *et al*. (2003), Friend *et al*. (2003), Cawood *et al*. (2007), Kirkland *et al*. (2008), Waldron *et al*. (2008), McAteer *et al*. (2010), Cawood *et al*. (2012), Strachan *et al*. (2013), Waldron *et al*. (2014) and Johnson *et al*. (2016). Data from samples interpreted from Cadomia-Armorica are from Fernandez-Suarez *et al*. (2002), Samson *et al*. (2005), Linnemann *et al*. (2008) and Strachan *et al*. (2008). Data from sample of Ganderian association are from Fyffe *et al*. (2009), Waldron *et al*. (2014) and Willner *et al*. (2014). Data from samples interpreted to be of Megumian affinity are from Krogh & Keppie (1990), Waldron *et al*. (2009, 2011) and

Pothier *et al*. (2015). \`East' Avalonia data were taken from Collins and Buchan (2004), Murphy *et al*. (2004b), Strachan *et al*. (2007), Linnemann *et al*. (2012) and Willner *et al*. (2013). Data from samples interpreted to be sourced from \`West' Avalonia are from Keppie *et al*. (1998), Thompson & Bowring (2000), Barr *et al*. (2003), Murphy *et al*. (2004a, 2004b), Pollock (2007), Satkoski *et al*. (2010), Thompson *et al*. (2012), Dorais *et al*. (2012); Barr *et al*. (2012), Force & Barr (2012), Pollock *et al*. (2012), Willner *et al*. (2013) and Henderson *et al*. (2016). Caledonian granite ages are from Ireland only and include various isotopic geochronological techniques. The granite data were sourced from a compilation by Chew & Stillman (2009).

Sample separation was undertaken at Vrije Universiteit Amsterdam. Detrital zircons were liberated from samples using a jaw crusher and disc mill. Density separation was achieved using diiodomethane in a centrifuge as per Ijlst (1973) and magnetic separation using a Frantz magnetic separator. Zircons of all morphologies and colours, between 60 and 250 µm, were hand-picked under binocular microscope. Typically, between 120 and 180 zircons per sample were mounted in epoxy disks and ground and polished to expose the approximate centre of the grains. Cathodolumenescence (CL) imaging was undertaken at the University of St. Andrews and at Trinity College Dublin in order to identify optimal positions for laser ablation.

Uranium, thorium and lead isotopes were measured by laser ablation-sector field-inductively coupled plasma-mass spectrometry (LA-SF-ICP-MS) at the Museum für Mineralogie und Geologie (Geoplasma Lab, Senckenberg Naturhistorische Sammlungen Dresden) using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. Each analysis consisted of approximately 15 s background acquisition followed by 30 s data acquisition. A common-Pb correction based on the interference- and background-corrected ^{204}Pb signal and a model Pb composition (Stacey & Kramers 1975) was carried out if necessary. The necessity of the correction is judged on whether the corrected ^{207}Pb/^{206}Pb lies outside of the internal errors of the measured ratios. Raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependant elemental fractionation of Pb/Th and Pb/U using a Microsoft Excel spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Geothe-University Frankfurt, Frankfurt am Main, Germany). Concordia diagrams and concordia ages were produced using Isoplot/Ex 3.7 of Ludwig (2012). Frequency and kernel density estimation (KDE) curves were plotted using DensityPlotter (Vermeesch 2012). Frequency plots were assigned a binwidth of 25 Ma. KDEs were plotted using a bandwidth of 20 Ma and a Gaussian kernel. This bandwidth was chosen by trial and error (by comparison to histograms and probability density plots) because in many cases the ‘optimal bandwidth’ calculated in DensityPlotter caused severe oversmoothing. More importantly, the same bandwidth was applied to all samples and to detrital zircons from potential source areas so that comparisons were like-for-like. Multi-dimensional scaling (MDS) analysis was performed using the R package `provenance` by Vermeesch *et al*. (2016).

White mica Ar-Ar

Detrital white mica Ar-Ar ages for the Coumeenoole Formation in the Dingle Group from Ennis *et al.* (2015) are recalculated in this study using the 28.201 ± 0.046 Ma age of Kuiper *et al.* (2008) for the Fish Canyon sanidine standard, generally increasing the age of individual grains by ca. 1 % . This was done to facilitate comparison of future detrital white mica analyses which will be conducted using this age for the standard. Details of analytical procedures can be found in Ennis *et al.* (2015).

Apatite U-Pb

At each outcrop, ~10 kg of material was collected across several adjacent beds to reduce any bias arising during deposition from localized heavy mineral concentrating processes. Subsequent sample preparation and analysis were conducted at Trinity College Dublin. The sub–300 μm nonmagnetic heavy mineral fraction was obtained by standard jaw crushing, sieving, magnetic, and heavy liquid separation techniques. Grains were mounted in epoxy resin, ground to expose internal surfaces, and polished. To avoid sample bias, no attempt was made to exclude anhedral or inclusion-bearing grains; the LA-ICP-MS technique permits identification and exclusion of U-rich inclusions (e.g., zircon) from the time-resolved (i.e., downhole) ablation signal of the appropriate isotopes.

Analyses were conducted using a Photon Machines Analyte Excite 193 nm ArF Excimer laser ablation system coupled to a Thermo Scientific iCAP Qc ICPMS, employing laser spots of 30 μm, a fluence of 4.5 J cm^{-2}, a repetition rate of 5 Hz, and an ablation time for each spot of 45 s followed by a 25 s background measurement. Repeated measurements of the primary Madagascar apatite mineral standard (Thomson *et al.* 2012) were used to correct for downhole U-Pb fractionation, mass bias, and intrasession instrument drift using the “VizualAge_UcomPbine” data reduction scheme for IOLITE (Chew *et al.* 2014; Paton *et al.* 2011), while the secondary McClure Mountain and Durango apatite standards were analysed as unknowns (Schoene & Bowring 2006; McDowell *et al.* 2005). Unlike phases that exclude common (initial or nonradiogenic) Pb during crystallization, such as zircon, the often high common-Pb content in apatite typically renders apatite grains discordant in the U-Pb system. Common-Pb in the Madagascar apatite primary standard was corrected for using a ^{207}Pb-based correction method using a known initial ^{207}Pb/^{206}Pb ratio (Chew *et al.* 2014). Variable common-Pb content in the detrital apatite unknowns was corrected using an initial common-Pb composition derived from a terrestrial Pb evolution model (Stacey & Kramers 1975) applied to an initial estimate for the age of the apatite, and then by adopting an iterative approach based on a ^{207}Pb correction (Chew *et al.* 2011). The ^{207}Pb-based correction assumes U-Pb* (radiogenic Pb) concordance – a reasonable assumption in the case of standards and magmatic grains, but one which may not be the case for detrital grains that have experienced partial Pb loss. As a result, independent geological evidence is required to discriminate between partially and wholly reset detrital U-Pb ages, similar to partially reset AFT ages (Mark *et al.* 2016).

Due to the ^{207}Pb-based correction, no apatite U-Pb age data can be excluded based on discordance criteria. However, the relatively low U content of apatite (sometimes <1 ppm) and consequent near-zero radiogenic Pb content of some grains can result in undesirably large analytical uncertainties. We therefore excluded grains with 2σ errors >25%, similar to the approach of Zattin *et al.* (2012).

As post-deposition temperatures exceeded the thermal sensitivity of the AFT technique (ca. 120-60 °C; e.g., Gallagher *et al.* 1998), the resultant AFT ages typically defined a single population for each sample. Because only a single AFT age population was defined for each sample, it was only necessary to analyse ca. 20-30 grains for each sample.

Detrital zircon U-Th-Pb results

Two hundred and seventy three zircons were analysed from the Lower Devonian Dingle Group on the Dingle Peninsula. Another 119 detrital zircon grains were analysed from the Upper Devonian Slieve Mish Group on the Dingle Peninsula. The number of concordant ages obtained from each sample ensures an extremely low probability of missing an age component that contributes 10 % of the detrital zircon age population of the analysed sediment (Vermeesch *et al*. 2016). For all three samples, where age populations contribute over six percent, interpretations can be made at the 95 % confidence level.

Age uncertainties reported in the text are at the 2σ level unless otherwise stated. Core-rim analyses were undertaken where these features could be identified in CL images and where grains were large enough. Only rim ages are used for provenance interpretations in order to determine the most recent source of sediment. The results are presented as Wetherill concordia (Wetherill 1956), frequency and KDE plots (Figs 4 and Fig. 5). The $^{207}Pb/^{206}Pb$ age is reported where the $^{206}Pb/^{238}U$ age is greater than 1.0 Ga because the $^{207}Pb/^{206}Pb$ age is more precise in older zircon grains (e.g. Gehrels *et al*. 2008).

Coumeenoole Formation - Sample AK19

Sample AK19, collected at Connor Pass, consists of grey, moderately sorted, medium- to coarse-grained sandstone and is the stratigraphically oldest sample in the study area. One hundred and fourteen zircon grains were analysed yielding a total of 86 concordant analyses ranging from 394 ± 9 Ma to 2142 ± 16 Ma (Fig. 4a). Thirty seven grains (43 %) yielded Mesoproterozoic ages which form a major peak at around 1.20 Ga (Fig. 5a). Neoproterozoic zircons make up 26 % (n = 22) of the sample, the second largest peak in the sample occurring at around 550 Ma. The rest of the sample is composed of 14 (16 %) Palaeoproterozoic zircons and 13 (15 %) Palaeozoic zircons. Of the Palaeozoic grains, four are Cambrian, four are Ordovician, two are Silurian and three are Devonian. Two of the Devonian zircons, the youngest in the sample, have ages of 394 ± 9 Ma and 402 ± 10 Ma and have length:width ratios of 3:1 and 5:1 respectively. Kostov (1973) suggests that high length-width ratios may indicate rapid cooling rates. However, such ratios may simply represent first order detrital zircons that have not been reworked (Poldervaart 1955).

Slea Head Formation - Sample AK21

This sample was taken from Cooleen Pier in Ventry Bay and consists of dark grey, medium- to coarse-grained, pebbly sandstones. Ninety eight concordant ages were obtained from measurement of 159 zircon grains. Ages range from 395 ± 8 Ma to 2765 ± 29 Ma and the largest peak is developed at 1.18 Ga (Figs Fig**. 4**b and Fig**. 5**b). Mesoproterozoic zircons form the bulk of the sample at 40 % (n = 39). Twenty six zircon grains (27 %) are Neoproterozoic in age, forming a major peak at ca. 630 Ma. Palaeoproterozoic zircons contribute 13 % (n = 13) of the sample. Eighteen grains are Palaeozoic in age, including one Cambrian zircon, eight Ordovician zircons, three Silurian zircons and six Devonian zircons. This sample, unlike AK19, also contains Archaean grains (n = 2). A concordia age of 405 ± 4 Ma ($MSWD_{conc}$ = 0.18; p_{conc} = 0.67) was calculated using the six Devonian zircons. Two of these zircons display length:width ratios of greater than 3:1.

Cappagh Sandstone Formation - Sample AK17

This sample, consisting of grey to pink, poorly sorted medium- to coarse-grained, pebbly sandstone, was taken from an outcropping ridge at Aughils, north of the R561. One hundred and nineteen zircons were analysed, producing 84 concordant ages ranging from 403 ± 9 Ma to 3677 ± 21 Ma (Fig. 4c). The majority of these grains are Mesoproterozoic in age (43 grains representing 51 % of the sample) and the largest peak in the sample is Mesoproterozoic at ca. 1.05 Ga (Fig. 5c). Sixteen grains (19 %) are Palaeoproterozoic in age and represent the second largest population in the sample. Neoproterozoic zircons represent 12 % (n = 10) of the sample. Palaeozoic zircons represent 10 %, including one Cambrian zircon, three Ordovician zircons, three Silurian zircons and one Devonian zircon. Seven Archaean zircon grains are present in the sample. There is a paucity of zircon ages (n = 3) between ca. 550 Ma and ca. 980 Ma.

Apatite U-Pb and Mica ^{40}Ar/^{39}Ar Geochronology

Apatite U-Pb

These data were generated concurrently with apatite fission track analyses that were undertaken for bedrock thermal history studies by Cogné *et al.* (2014), but were not previously published. Due to the low number of detrital apatite grains analysed, the data must be interpreted with caution. In some cases, samples from the same formation are combined to yield the minimum statistical requirement of 60 analyses, as per Dodson *et al.* (1988). The limited variability in detrital apatite ages in these larger samples suggests that it is unlikely that multiple apatite sources of significantly different age and thermal history were being sampled by the sediments under investigation. The apatite U-Pb ages were not utilised in the aforementioned study. Therefore the data have been included in this study (**Fig. 6**) to provide a geochronological proxy which has an intermediate closure temperature (ca. 375-550 °C; Cochrane *et al.* 2014) between the mica ^{40}Ar/^{39}Ar and zircon U-Pb systems. The sampling transect was collected from Mount Brandon on the Dingle Peninsula (Fig. 3). This transect intersected two formations and includes four samples taken from the Ballymore Sandstone Formation and one sample from the Farran Sandstone Formation.

Combined analyses from four samples (Mb-1, Mb-4, Mb-5 and Mb-7) from the Ballymore Sandstone Formation, the uppermost formation in the Dingle Group, yields a KDE spectrum composed of 70 ages forming a single KDE peak at ca. 420 Ma. Detrital apatite ages in this formation range from 356 ± 80 to 896 ± 30 Ma (Fig. 6a). However, 63 % of grains have ages between 380 and 440 Ma and 10 % have ages of less than 393 Ma (end-Emsian). Eighteen apatite grains were analysed from the Farran Sandstone Formation (sample Mb-9), the lowest formation in the Smerwick Group. These grains range in age from 347 ± 58 to 1356 ± 227 Ma. The KDE spectrum (Fig. 6b) shows the highest age concentration at ca. 420 Ma.

Mica $^{40}Ar/^{39}Ar$

Ennis *et al.* (2015) acquired detrital white mica ages for a sample from the Coumeenoole Formation, at a similar location (Connor Pass) to detrital zircon sample AK19. These ages have been recalculated here using the revised Fish Canyon standard age of Kuiper *et al.* (2008). Detrital white mica ages in the sample range from 308 ± 10.3 Ma to 440 ± 7 Ma, including two main age groups forming KDE peaks at ca. 414 Ma and ca. 382 Ma (**Fig. 7**).

Discussion

The overall age distribution of detrital zircons in samples from the Coumeenoole and Slea Head formations (similar Proterozoic distributions, a gap in ages between 730 and 940 Ma, mostly continuous distributions between 390 and 730 Ma and major KDE peaks at around 1.2 Ga) suggests a common source throughout their deposition (Kolmogorov-Smirnov test p-value of 0.871). Palaeozoic peaks in both samples, at around 430 Ma, likely correspond to a Caledonian (430-420 Ma) source.

A mean $^{207}Pb/^{206}Pb$ age of 432 ± 3 Ma as well as a whole-rock Rb-Sr isochron age of 428 ± 11 Ma was obtained by O'Connor *et al.* (1988) for the Carnsore granite. A Rb-Sr whole-rock isochron age of 436 ± 7 Ma for the Saltees granite by Max *et al.* (1979) led O'Connor *et al.* (1988) to conclude that the two intrusions are genetically related. These intrusions are the only ones of this age in Ireland and the 430 Ma age of detrital zircons from the LORS, as well as the northerly directed palaeoflow of the Trabeg Conglomerate Formation (Todd 2000), suggests that the intrusions extend westward beneath the Munster Basin along the strike of Caledonian lineaments. The idea of such a buried granite is not new; it was first proposed by Murphy (1960) and has since been expanded upon by a number of authors (e.g. Ford *et al.* 1991; Meere 1995; Masson *et al.* 1998; Vermeulen *et al.* 2000; Todd 2000). Vermeulen *et al.* (2000) interpreted seismic profiles across southern Ireland as showing a shallow, granitic body buried beneath the UORS just south of the Killarney-Mallow Fault Zone. Todd (2000) suggested that granite clasts within the Trabeg Conglomerate Formation might represent the unroofing of a presently buried granitic intrusion which forms part of an extension of the Leinster Massif.

Detrital apatite ages from the uppermost part of the Dingle Group, in the Ballymore Formation, yield a single peak at ca. 420 Ma (**Fig. 6**a) which is compatible with a Late Caledonian granitic source. Williams *et al.* (1999) obtained an age of 411 Ma for the Cooscrawn Tuff Bed in the Ballymore Formation which is older than 22 of the 70 detrital apatites analysed in this formation. A concordia age from six zircons in the underlying Slea Head Formation provides a minimum depositional age of 405 ± 4 Ma ($MSWD_{conc}$ = 0.18; p_{conc} = 0.67) and suggests that the Cooscrawn Tuff age is likely erroneous. Palynological evidence places the deposition of the Slea Head Formation in early to possibly middle Emsian times and is compatible with the youngest group of detrital zircons in this formation. The high length to width ratio of some of the youngest zircons in both the Coumeenoole and Slea Head formations may suggest an igneous source that had cooled rapidly (Kostov 1973) – possibly a syn-sedimentary volcanic source. Although U-Pb ages of apatite grains from the Ballymore Formation are younger, they are nonetheless indistinguishable from the zircon ages of the Coumeenoole and Slea Head formations at the 2-sigma level. A dominant age peak of ca. 420 Ma (**Fig. 6**b) is also observed for 17 detrital apatite grains in the Farran Sandstone Formation (Smerwick Group) which unconformably overlies the Ballymore Formation.

A lower Palaeozoic source of detrital mica is reflected in the oldest age peak (ca. 414 Ma, **Fig. 7**) from a sample from the Coumeenoole Formation. However, the dominant age peak is much younger, at ca. 382 Ma. This peak is much younger than the Emsian depositional age of the host sedimentary rock and suggests that the LORS experienced a thermal resetting event. A review of the potential causes of resetting is provided in Ennis *et al.* (2015) and the extension associated with Lough Guitane Volcanism in the Munster Basin is briefly mentioned. Given that Williams *et al.* (2000) obtained a U-Pb zircon age of 378.5 Ma for the Horses Glen Volcanic Centre and 384.5 Ma for the Killeen Volcanic Centre (which lie to the southeast of the Dingle Basin), it is likely that the younger detrital mica ages represent resetting by high heat flow associated with extension and volcanism which may have been caused by emplacement of a granitic body at depth below the Munster Basin (Avison 1984). Alternatively, these younger ages could represent partial resetting due to low-grade Variscan metamorphism at the end of the Carboniferous Period.

The low proportion of Palaeozoic zircons in the Dingle Group does not reflect the high proportion of volcanic clasts reported by Todd (2000) and interpreted to have been derived from rocks of Ordovician to Silurian age. This, however, may simply be a function of low zircon fertility in the volcanic source due to the dominant mafic to intermediate compositions (Todd 2000).

Determination of the ultimate source of late Neoproterozoic detrital zircons in these samples is relatively straightforward because of the lack of abundant known sources of this age on this part of the Laurentian craton (Fig. 2). The LORS samples also contain some 1.9 to 2.1 Ga zircons, considered to be indicative of the Gondwanan Eburnean Orogeny (Nance *et al.* 2008). Late Neoproterozoic zircons are ubiquitous in peri-Gondwanan terranes as a result of arc magmatism at that time (Nance *et al.* 2008) and therefore represent the most likely source. It should be noted, however, that Cawood & Nemchin (2001) report extensional magmatism associated with rifting in Laurentia between 520 and 555 Ma. But sedimentary rocks interpreted to be of Laurentian affinity do not record extensive Neoproterozoic zircon production (Fig.Fig. 2). Combined detrital zircon ages from various Cambrian formations in the Leinster Massif (Waldron *et al.* 2014) yield a high proportion in the range 500 to 770 Ma forming a peak at around 590 Ma (**Fig. 8**d). Waldron *et al.* (2014) proposed that these zircon ages represent a Ganderian source for the host sediments. If the source of granitic material for the Dingle Group was indeed Late Caledonian granites as suggested above, then, by extension, the Cambrian to Ordovician rocks into which the granites intrude are also a viable source of detritus. Support for derivation of late Neoproterozoic zircons from recycling of peri-Gondwanan sediments can be found in the study by Todd (2000) who found coticule and tourmalinite clasts akin to rocks found in the Ordovician Ribband Group. Todd (2000) also suggests that quartzite clasts in the Trabeg Conglomerate Formation could be related to quartzites of the Cambrian Bray Group. The similarity in the ranges of detrital zircon ages younger than 800 Ma in both the Coumeenoole and Slea Head formations suggests that this southerly source remained available throughout their deposition.

Zircons with ages in the range of 1.1 to 1.25 Ga, the most abundant in both samples, are likely ultimately sourced from Laurentia. Cawood and Nemchin (2001) consider grains in this age range to be representative of magmatic and metamorphic activity associated with the Grenville Orogeny. Zircons of similar age are present in the Ganderia-derived Cambrian sediments in the Leinster Massif. However, the far greater abundance of zircons of this age range relative to zircons of late Neoproterozoic age in the Dingle Group samples requires an additional source from which the older zircons can be derived.

Constructing a palaeodrainage pattern for the Coumeenoole and Slea Head formations requires a source (or sources) of detritus that meet the following criteria:

a) Abundant zircons yielding ca. 1.2 Ga U-Pb ages (likely of ultimate Laurentian affinity).
b) Presence of late Neoproterozoic and 1.9 to 2.1 Ga zircons (of peri-Gondwanan affinity)
c) Paucity of zircons between 730 and 940 Ma
d) Low proportion of Palaeozoic zircons
e) Late Caledonian apatite U-Pb and white mica $^{40}Ar/^{39}Ar$ ages (ca. 420 Ma and 414 Ma, respectively).

Transverse drainage, as indicated by palaeocurrent directions (Todd 2000), particularly from the south but possibly also from the north, was the likely means by which Late Caledonian and peri-Gondwanan material was supplied to the Dingle Basin (**Fig. 9**). Evidence of Late Caledonian detrital input to the basin is given by 420

Ma apatite and 414 Ma mica ages. Although the ultimate source of Mesoproterozoic zircons in the Coumeenoole and Slea Head formations was probably the Grenville Orogeny, defining the immediate source area is more problematic because a source of abundant 1.2 Ga zircons has not been found in Ireland. Ordovician and Silurian sediments from the Southern Uplands – Longford Down terrane show an abundance of 1.1 Ga (**Fig. 8**a and **Fig. 8**c) and Ordovician zircons (**Fig. 8**b). This accretionary wedge material is therefore a poor candidate unless the source character of these sedimentary rocks changes westward, along strike. The apparent dissimilarity, revealed by multi-dimensional scaling analysis, between the Dingle Group samples and samples of Laurentian derivation in the Southern Uplands – Longford Down terrane (**Fig. 8**g) reflects the lack of 1.2 Ga zircons in the available source data and presence of late Neoproterozoic zircons of peri-Gondwanan affinity in the Dingle Group samples.

Given the bulk northeastward palaeoflow in the Coumeenoole and Slea Head Formations (Todd *et al.* 1988), it is likely that most of the detritus was deposited as a result of this flow. A source to the southwest of the Dingle Basin must account for the high proportion of Laurentian zircons in the analysed samples. Therefore, although the main river course likely flowed from the west and southwest, we suggest that Caledonian highlands in the north produced a large number of tributaries flowing from north to south, into the main Coumeenoole/Slea Head system (Fig. 9). Alternatively, it is also possible that the Iapetus Suture forms a regional S-shape and that the strike of the suture swings from roughly east-west onshore to southwest-northeast off the southwest coast of Ireland. This is highly speculative however, as there is no other supporting evidence for such a hypothesis.

Unlike the LORS on the Dingle Peninsula, the UORS, represented by sample AK17 from the Cappagh White Sandstone Formation, contains very few late Neoproterozoic zircons but is instead dominated by Mesoproterozoic grains. Also unlike the LORS, the UORS contains a dominant 1.05 Ga peak as opposed to the 1.2 Ga peak of the LORS. The lack of late Neoproterozoic grains, dominant 1.05 Ga KDE peak and similarity to detrital zircon age spectra of Laurentian affinity (**Fig. 8**a, **Fig. 8**c and **Fig. 8**g) indicates a northerly-derived source area and no input from sources south of the Iapetus Suture. It would also indicate that recycling of the LORS into the UORS in southern Ireland, as previously suggested, is not likely to have occurred. It is more conceivable that this sediment was recycled from material similar to that found in the Longford Down terrane.

It is becoming widely accepted that a period of regional sinistral transtension occurred across the Iapetus Suture Zone in the Early Devonian Period (Todd 1989; Phillips *et al.* 1995; Dewey & Strachan 2003; Brown *et al.* 2008; Cooper *et al.* 2016). In the present study, the discrepancy between 1.2 Ga Laurentian zircons found in the Dingle Group and 1.1 Ga Laurentian zircons found in the Longford Down and Southern Uplands terranes as well as the abundance of 1.05 Ga zircons in the UORS of the Dingle Peninsula is supportive of large-scale sinistral transtenional displacement along the Iapetus Suture, removing the 1.2 Ga source of detrital zircon and introducing the 1.05-1.1 Ga source to the UORS in the Late Devonian Period. Of course, this discrepancy may not have tectonic significance and may simply be representative of topographic separation of sources or complete denudation of the 1.2 Ga source and subsequent exhumation of the 1.1 Ga source. High resolution detrital zircon sampling of younger formations within and overlying the Dingle Group would serve to elucidate the nature and timing of the change in source character.

Finally, a minimum depositional age of ca. 405 Ma for the Coumeenoole Formation adds to growing evidence (Soper & Woodcock 2003, and references therein) of a discrete Emsian orogenic event in the British Isles.

Conclusions

This paper presents the first multi-proxy, single-grain detrital geochronological study of the LORS in the Lower Devonian Dingle Basin in southwestern Ireland which suggests the following:

1) The Dingle Basin sedimentary fill is dominated by Laurentian detritus but also includes a mixture of peri-Gondwanan and Late Caledonian (430-420 Ma) to Acadian (410-390 Ma) source areas.
2) A dominant drainage area lay to the west but the basin must have received much detritus from transverse drainage to the north which intersected Laurentian material.
3) Detrital zircons from the UORS Cappagh White Sandstone Formation show very different characteristics to the LORS where sediment was being supplied solely from detritus of Laurentian affinity.
4) The paucity of late Neoproterozoic zircons in the UORS compared to the high proportion in the LORS suggests that the UORS was not derived from recycling of LORS sediments as previously suggested.
5) Well documented regional sinistral transtension during the Early Devonian Period was likely responsible for a switch in Laurentian source character from the LORS (prevalence of 1.2 Ga detrital zircons) to the UORS (prevalence of 1.1 Ga detrital zircons).

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Figure Captions

Fig. 1. Regional map of the British Isles showing the major terranes of Ireland. The rectangle indicates the study area shown in Figure 3 (modified after McIlroy & Horák 2006; Waldron *et al.* 2014; McConnell *et al.* 2016; alternative ISZ after Todd *et al.* 1991). Inset: regional map showing broad tectonic domains (Linnemann *et al.* 2007; Nance *et al.* 2012; Waldron *et al.* 2014; Waldron *et al.* 2011; Waldron *et al.* 2009) Key: BT, Bellewstown Terrane; CG, Carnsore Granite; DB, Dingle Basin; GG, Galway Granite; GT, Grangegeeth Terrane; ISZ, Iapetus Suture Zone; NIC, Newry Igneous Complex; SG; Saltees Granite; TIC, Tyrone Igneous Complex.

Fig. 2. Kernel density plots (bandwidth = 20 Ma) of published detrital zircon ages from various potential source terranes (modified and expanded after Pointon *et al.* 2012). Laurentia data from Cawood *et al.* (2003); Friend *et al.* (2003); Cawood *et al.* (2007); Kirkland *et al.* (2008); Waldron *et al.* (2008); McAteer *et al.* (2010); Cawood *et al.* (2012); Strachan *et al.* (2013); Waldron *et al.* (2014); Johnson *et al.* (2016).

Cadomia-Armorica data from Fernandez-Suarez *et al.* (2002); Samson *et al.* (2005); Linnemann *et al.* (2008); Strachan *et al.* (2008). Ganderia data from Fyffe *et al.* (2009); Waldron *et al.* (2014); Willner *et al.* (2014). Megumia data from Krogh & Keppie (1990); Waldron *et al.* (2009, 2011); Pothier *et al.* (2015). `East' Avalonia data from Collins & Buchan (2004); Murphy *et al.* (2004); Strachan *et al.* (2007); Linnemann *et al.* (2012); Willner *et al.* (2013). `West' Avalonia data from Keppie *et al.* (1998); Thompson & Bowring (2000); Barr *et al.* (2003); Murphy *et al.* (2004a, 2004b); Pollock (2007); Satkoski *et al.* (2010); Thompson *et al.* (2012); Dorais *et al.* (2012); Barr *et al.* (2012); Force & Barr (2012); Pollock *et al.* (2012); Willner *et al.* (2013); Henderson *et al.* (2016). Caledonian granite ages are from Ireland only and include various isotopic geochronological techniques. The Caledonian data are taken from Chew & Stillman (2009).

Fig. 3. Geological map and generalised north-south geological cross section of the Dingle Peninsula showing sample locations (modified after Todd 1989; Ennis *et al.* 2015). Detrital apatite and detrital zircon sample location marked by bold asterisks and white stars respectively.

Fig. 4. Wetherill concordia plots for all detrital zircon samples analysed in this study (youngest ages inset). (a) Coumeenoole Formation (sample AK19). (b) Slea Head Formation (sample AK21). (c) Cappagh Sandstone Formation (sample AK17).

Fig. 5. Detrital zircon age KDE, histogram plots and age percentage distribution plots from Dingle Peninsula samples. (a) Coumeenoole Formation (sample AK19). (b)

Slea Head Formation (sample AK21). (c) Cappagh White Sandstone Formation (sample AK17).

Fig. 6. KDE and histogram plots for detrital apatite U-Pb ages in (a) the Ballymore Formation and (b) the Farran Sandstone Formation.

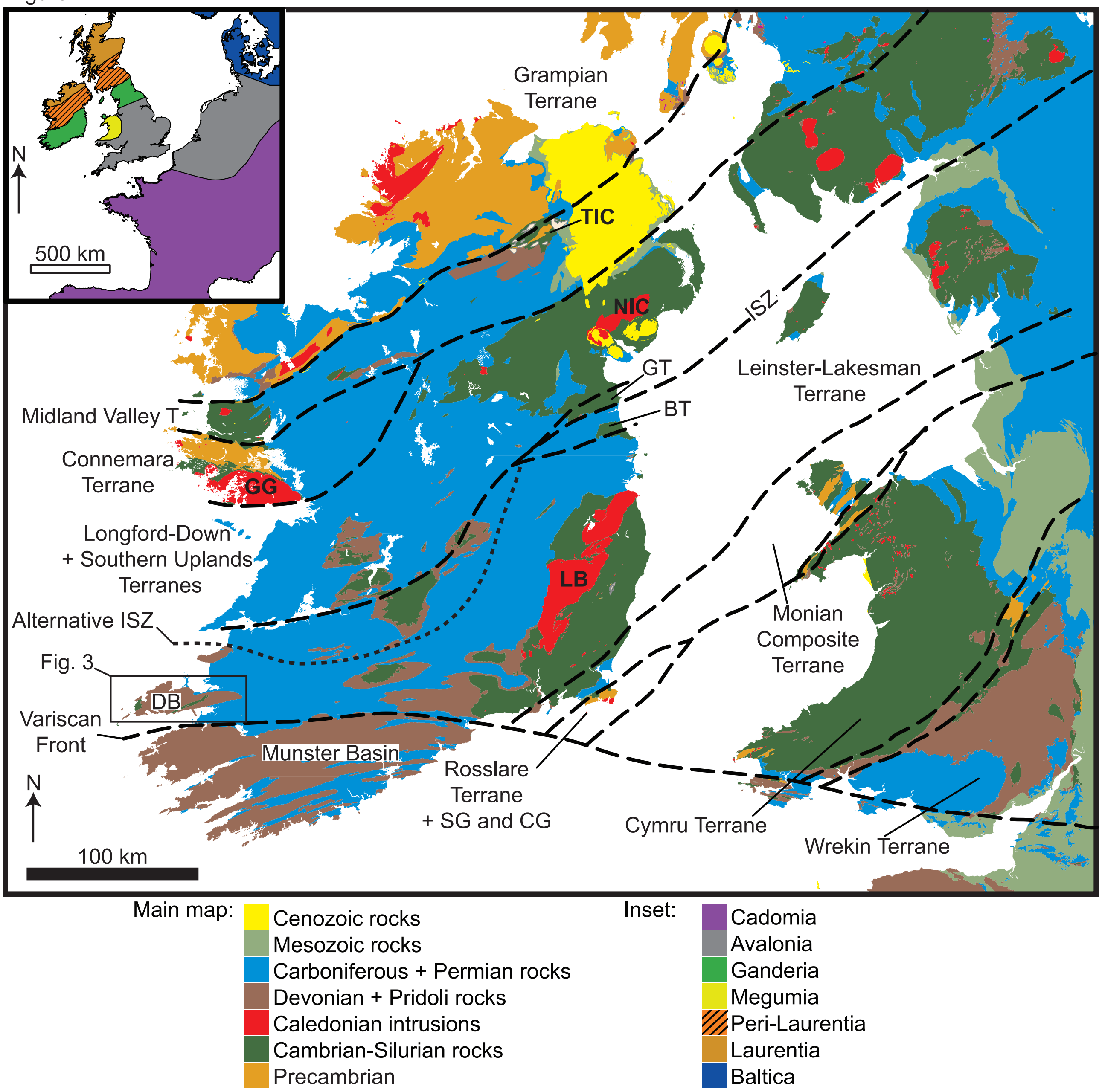
Fig. 7. Histogram and KDE plots of revised detrital white mica ages from a sample from the Coumeenoole Formation at Connor Pass on the Dingle Peninsula (original data from Ennis *et al.* 2015). Bold arrow represents approximate depositional age (see text for explanation of 382 Ma peak).

Fig. 8. KDE plots of detrital zircon ages from various potential local sediment sources as well as age distributions for detrital zircons analysed in this study. (a) Upper Ordovician to Llandovery sedimentary rocks of the Southern Uplands terrane (Waldron *et al.* 2008, 2014) with dominant Laurentian provenance. (b) Upper Ordovician to Llandovery sedimentary rocks of the Longford Down terrane showing peri-Laurentian arc provenance (McConnell *et al.* 2016). (c) A single sample from the Llandovery Lough Avaghon Formation in the Longford Down terrane showing dominant Laurentian provenance (McConnell *et al.* 2016). (d) Ganderian provenance of Cambrian sedimentary rocks in the Leinster terrane (Waldron *et al.* 2014). (e) UORS on the Dingle Peninsula. (f) Composite of two samples from the LORS Dingle Group. (g) Multi-dimensional scaling map of individual samples used in plots (a)-(f). Labels indicate broad provenance interpretations from original studies. Axes values are dimensionless K-S distances (Vermeesch 2013). The most closely related

samples are joined by a solid line and the second closest are marked with a dashed line. N, number of samples; n, number of single zircon grain ages.

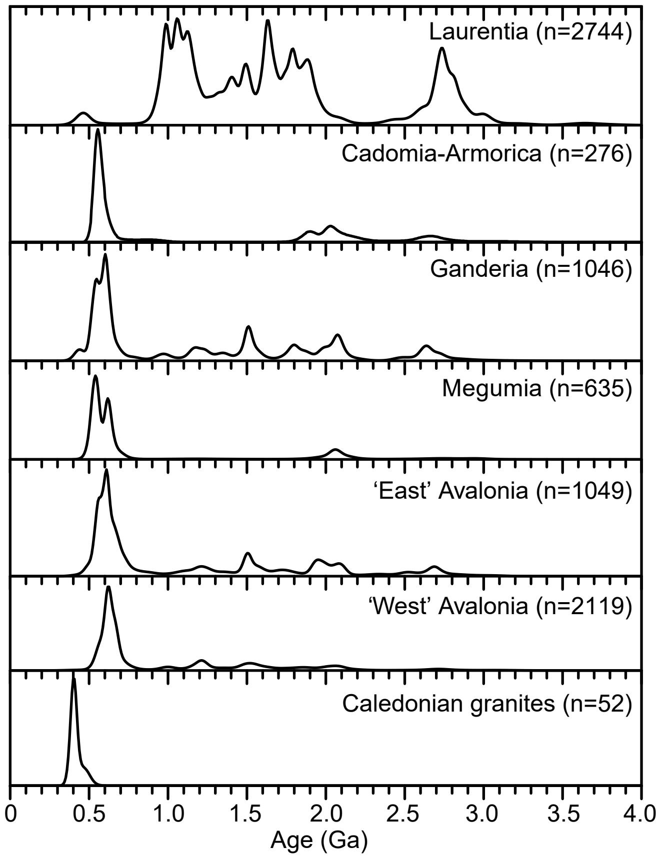
Fig. 9. Possible palaeodrainage pattern in the Dingle basin during deposition of the Coumeenoole and Slea Head Formations (modified after Todd 2000). CG, Carnsore Granite; DBL, Dingle Bay Lineament; GG, Galway Granite Batholith; LB, Leinster Batholith; NKL, North Kerry Lineament.

Figure 1



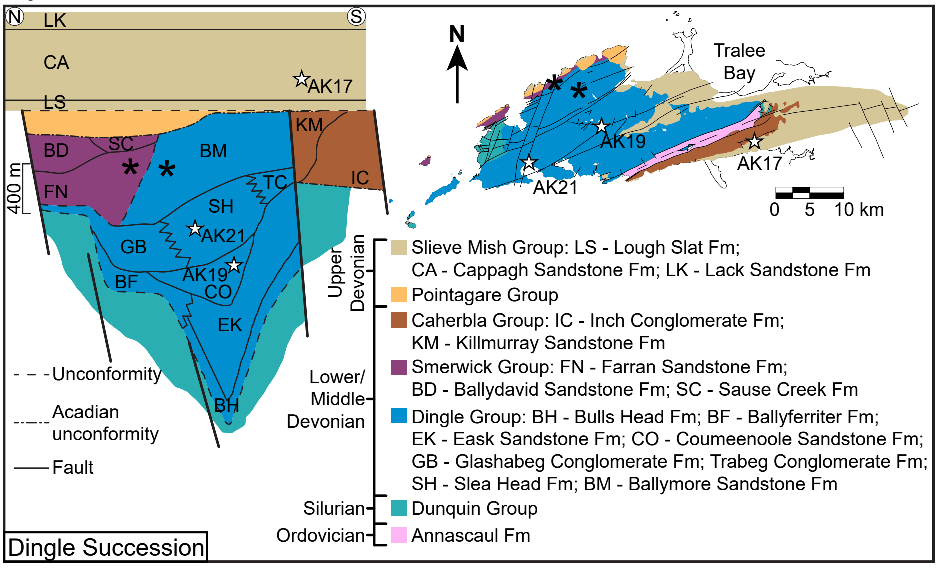
N
500 km
Grampian Terrane
TIC
NIC
GT
BT
ISZ
Leinster-Lakesman Terrane
Midland Valley T
Connemara Terrane
GG
Longford-Down + Southern Uplands Terranes
LB
Monian Composite Terrane
Alternative ISZ
Fig. 3
DB
Variscan Front
Munster Basin
Rosslare Terrane + SG and CG
Cymru Terrane
Wrekin Terrane
N
100 km
Main map:
Cenozoic rocks
Mesozoic rocks
Carboniferous + Permian rocks
Devonian + Pridoli rocks
Caledonian intrusions
Cambrian-Silurian rocks
Precambrian
Inset:
Cadomia
Avalonia
Ganderia
Megumia
Peri-Laurentia
Laurentia
Baltica

Figure 2



Laurentia (n=2744)
Cadomia-Armorica (n=276)
Ganderia (n=1046)
Megumia (n=635)
'East' Avalonia (n=1049)
'West' Avalonia (n=2119)
Caledonian granites (n=52)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Age (Ga)

Figure 3



N
S
LK
CA
LS
AK17
KM
IC
BD
SC
BM
FN
TC
SH
AK21
GB
AK19
BF
CO
EK
BH
400 m
Unconformity
Acadian unconformity
Fault
Tralee Bay
AK19
AK17
AK21
0 5 10 km
Upper Devonian
Lower/ Middle Devonian
Silurian
Ordovician
Slieve Mish Group: LS - Lough Slat Fm; CA - Cappagh Sandstone Fm; LK - Lack Sandstone Fm
Pointagare Group
Caherbla Group: IC - Inch Conglomerate Fm; KM - Killmurray Sandstone Fm
Smerwick Group: FN - Farran Sandstone Fm; BD - Ballydavid Sandstone Fm; SC - Sause Creek Fm
Dingle Group: BH - Bulls Head Fm; BF - Ballyferriter Fm; EK - Eask Sandstone Fm; CO - Coumeenoole Sandstone Fm; GB - Glashabeg Conglomerate Fm; Trabeg Conglomerate Fm; SH - Slea Head Fm; BM - Ballymore Sandstone Fm
Dunquin Group
Annascaul Fm
Dingle Succession

Figure 4

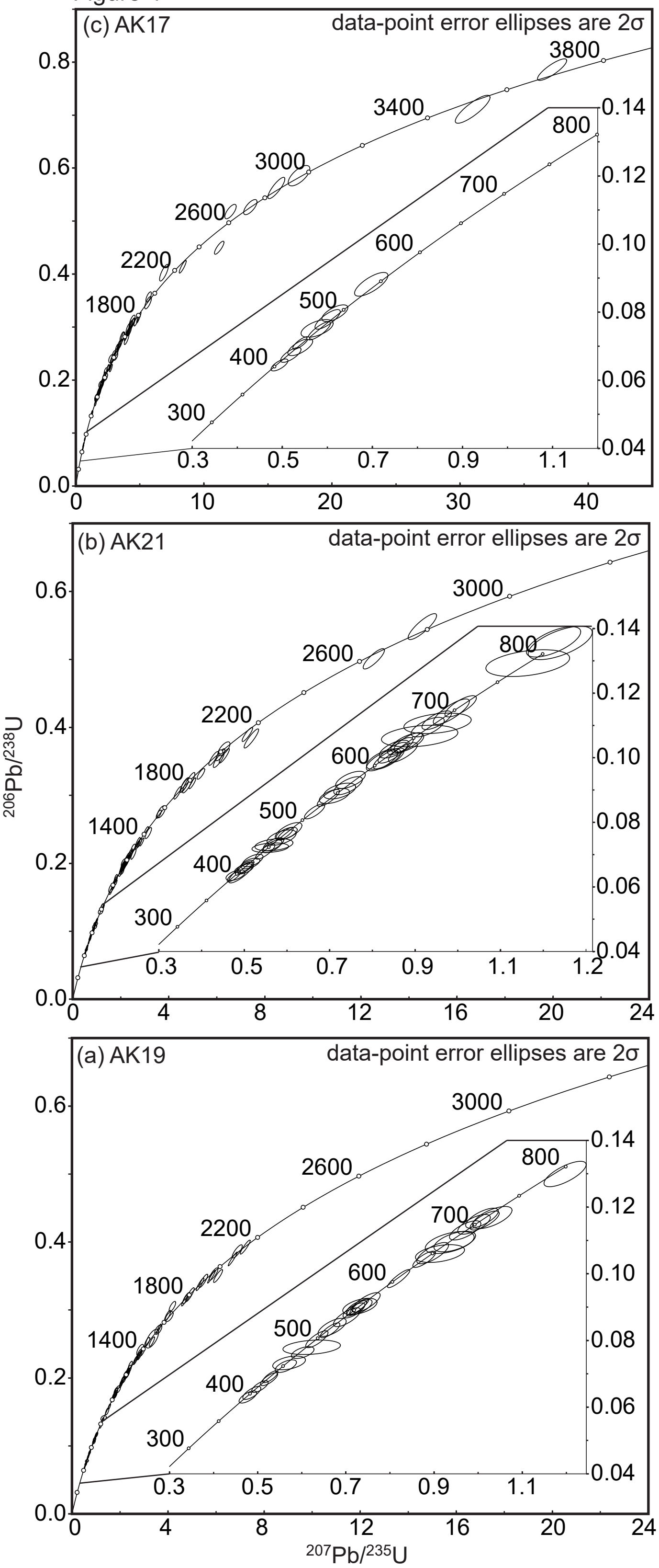
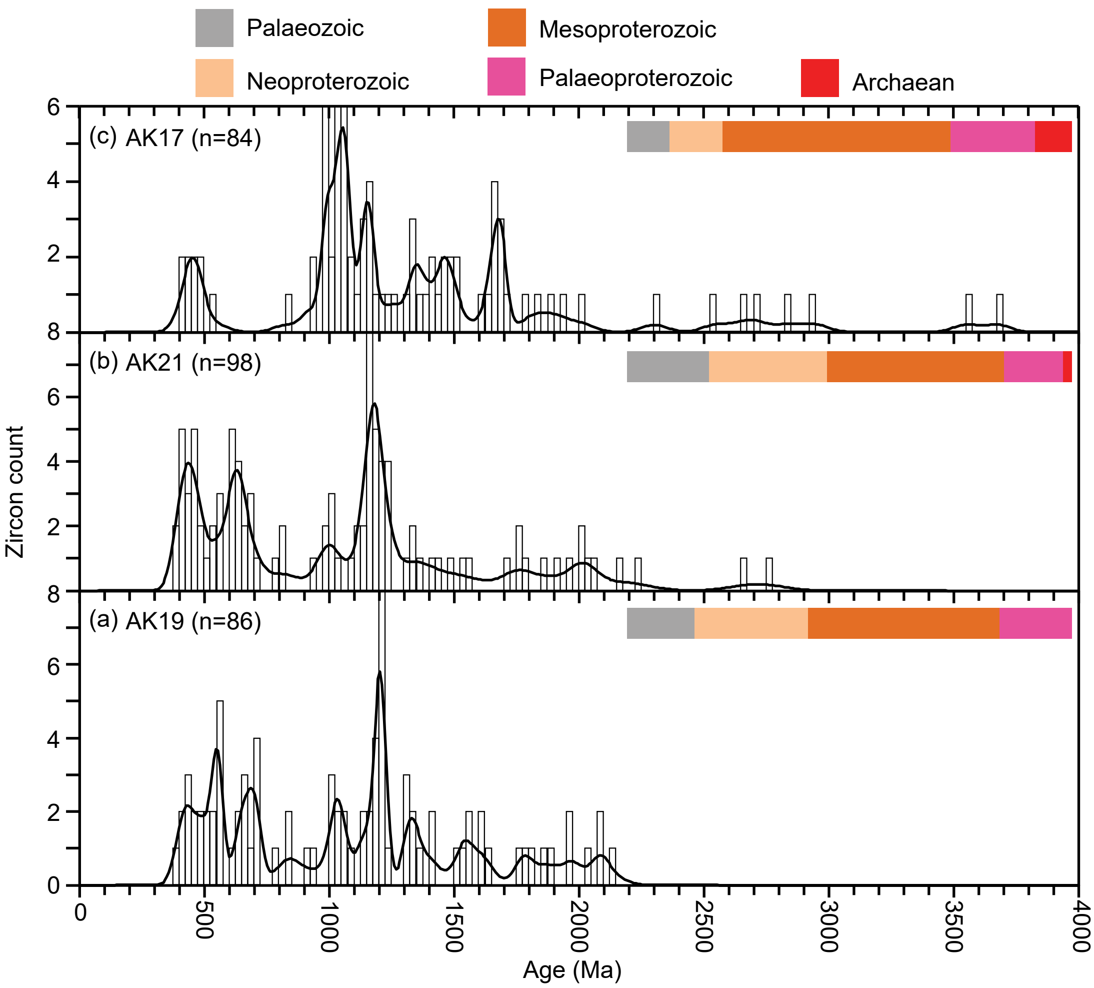
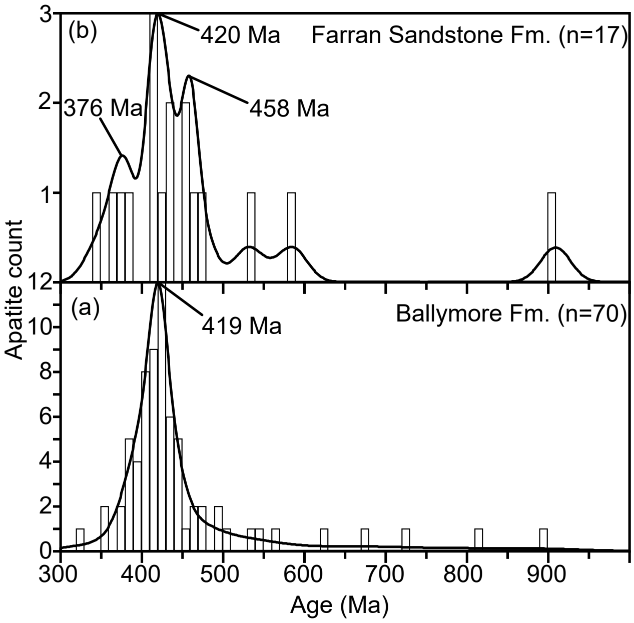

(c) AK17
data-point error ellipses are 2σ
3800
3400
3000
2600
2200
1800
800
700
600
500
400
300
(b) AK21
data-point error ellipses are 2σ
3000
2600
2200
1800
1400
800
700
600
500
400
300
(a) AK19
data-point error ellipses are 2σ
3000
2600
2200
1800
1400
800
700
600
500
400
300
206Pb/238U
207Pb/235U

Figure 5



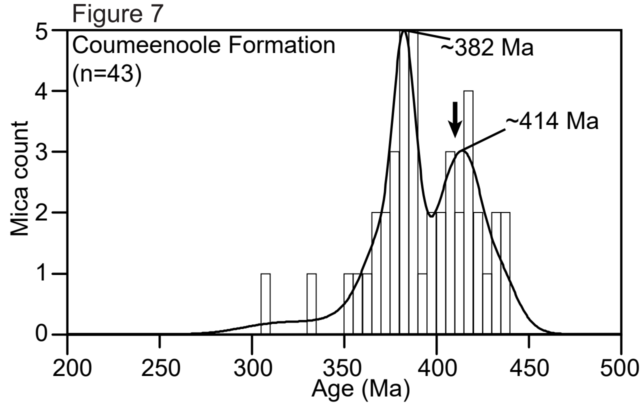
Palaeozoic
Mesoproterozoic
Neoproterozoic
Palaeoproterozoic
Archaean
(c) AK17 (n=84)
(b) AK21 (n=98)
(a) AK19 (n=86)
Zircon count
Age (Ma)
0
500
1000
1500
2000
2500
3000
3500
4000

Figure 6



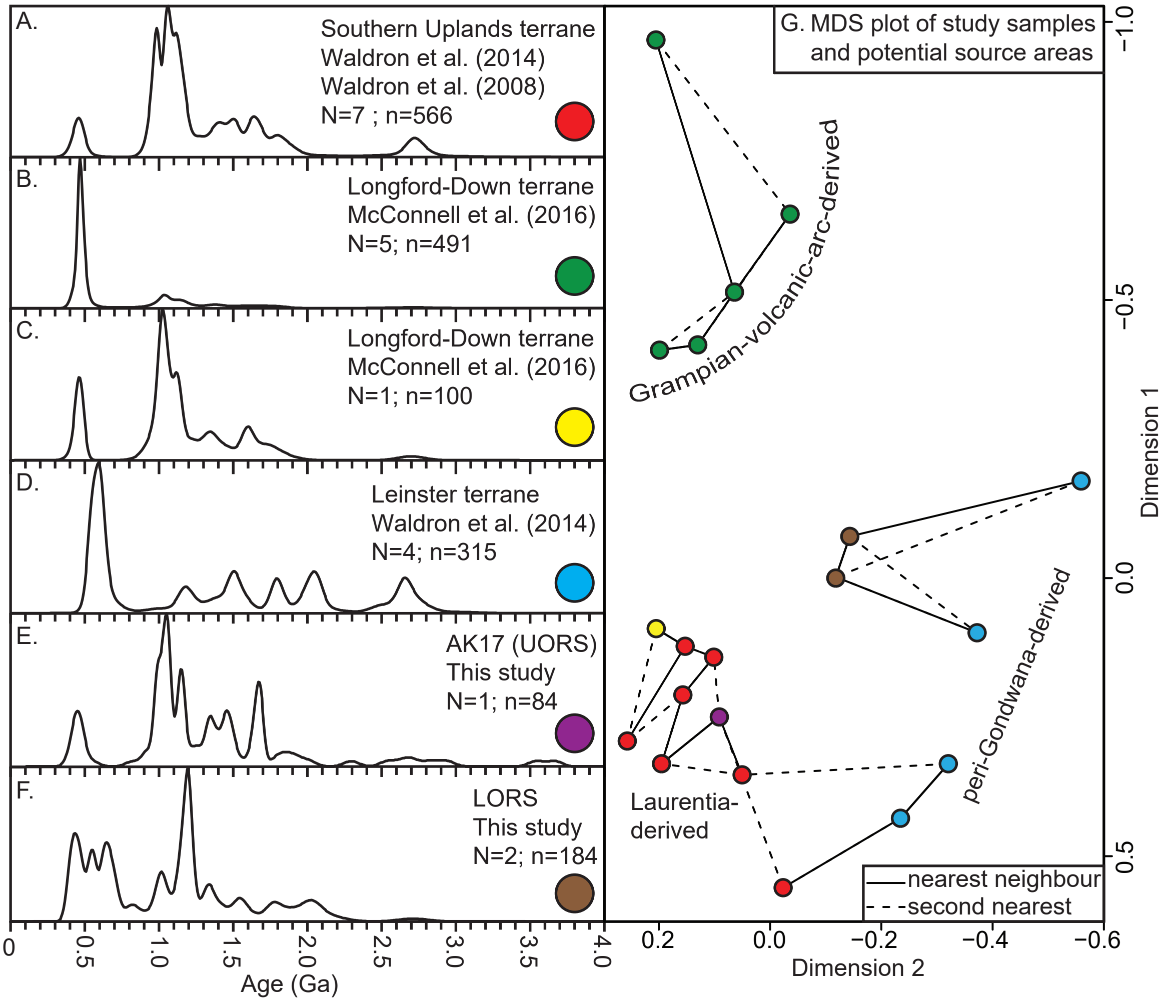
(b)
420 Ma
Farran Sandstone Fm. (n=17)
376 Ma
458 Ma
(a)
419 Ma
Ballymore Fm. (n=70)
Apatite count
Age (Ma)
300
400
500
600
700
800
900

Figure 7



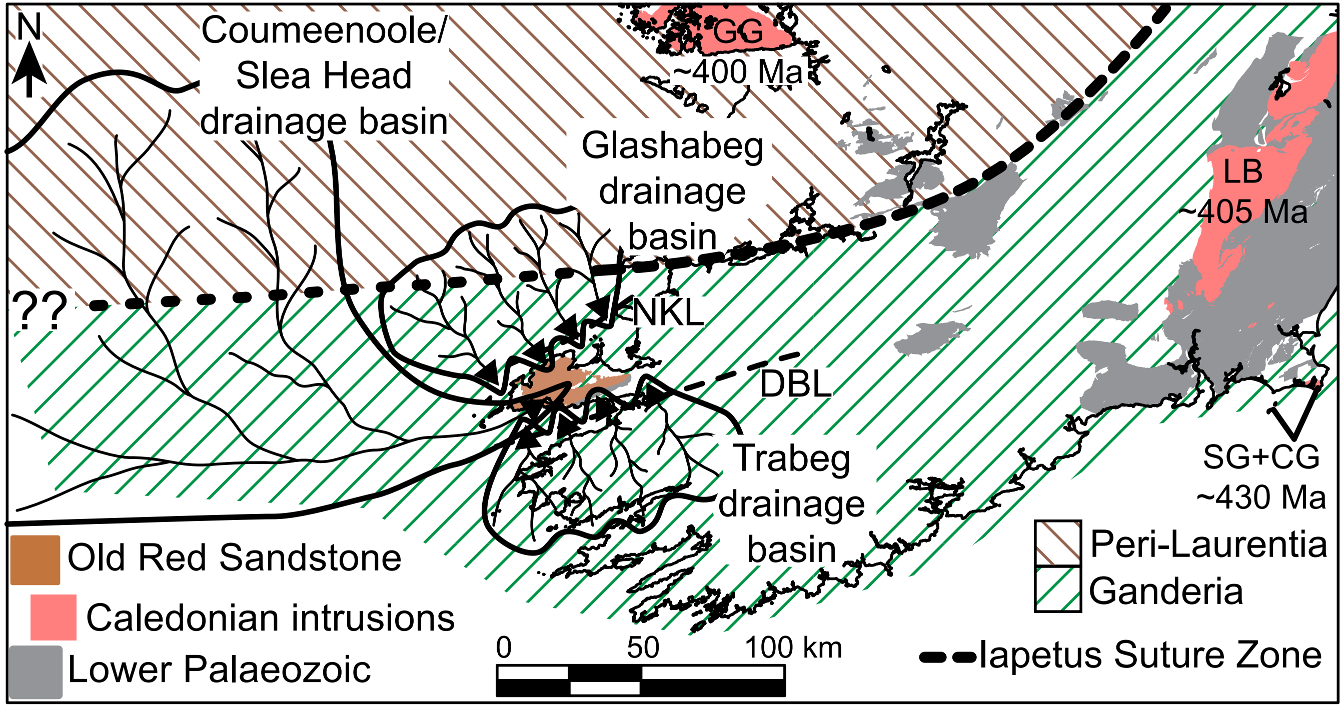
Coumeenoole Formation
(n=43)
~382 Ma
~414 Ma
Mica count
0
1
2
3
4
5
200
250
300
350
400
450
500
Age (Ma)

Figure 8



A.
Southern Uplands terrane
Waldron et al. (2014)
Waldron et al. (2008)
N=7 ; n=566
B.
Longford-Down terrane
McConnell et al. (2016)
N=5; n=491
C.
Longford-Down terrane
McConnell et al. (2016)
N=1; n=100
D.
Leinster terrane
Waldron et al. (2014)
N=4; n=315
E.
AK17 (UORS)
This study
N=1; n=84
F.
LORS
This study
N=2; n=184
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Age (Ga)
G. MDS plot of study samples
and potential source areas
Grampian-volcanic-arc-derived
peri-Gondwana-derived
Laurentia-
derived
nearest neighbour
second nearest
0.2
0.0
−0.2
−0.4
−0.6
Dimension 2
−1.0
−0.5
0.0
0.5
Dimension 1

Figure 9



N
Coumeenoole/
Slea Head
drainage basin
GG
~400 Ma
Glashabeg
drainage
basin
LB
~405 Ma
??
NKL
DBL
Trabeg
drainage
basin
SG+CG
~430 Ma
Old Red Sandstone
Caledonian intrusions
Lower Palaeozoic
0
50
100 km
Peri-Laurentia
Ganderia
Iapetus Suture Zone